

# **A MODEL FOR PREDICTING THE ENERGY PERFORMANCE OF EXISTING BUILDINGS UPGRADED WITH SUSTAINABLE TECHNOLOGIES**

**JOHN DADZIE**

BSc (Hons), MCPM (Thesis)

A thesis submitted in partial fulfilment of the requirements of the University of  
Technology Sydney for the degree of Doctor of Philosophy

August 2018

## **CERTIFICATE OF ORIGINAL AUTHORSHIP**

I, John Dadzie, declare that this thesis, submitted in fulfilment of the requirements for the award of Doctor of Philosophy in the Faculty of Design, Architecture, and Building at the University of Technology Sydney.

This thesis is wholly my own work unless otherwise referenced or acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

Signature of Candidate: .....

Date: .....

## **ACKNOWLEDGEMENTS**

I am grateful to my supervisors, Adjunct Professor Goran Runeson and Associate Professor Grace Ding, for their direction, patience, guidance, encouragement and sense of humour which have led to the successful completion of this research. To these special people who shaped me throughout my studies, I say, God bless you.

Sincere thanks are also extended to Professor D. K. Ahadzie of Kwame Nkrumah University of Science and Technology in Ghana for his encouragement and advice in undertaking this research.

I also acknowledge all staff of the Built Environment especially the Head of School, Professor Heather MacDonald for her immense support during the difficult times of my studies. God bless you for your kindness and unflinching support. Sincere gratitude to Ann Hobson, research manager of the Faculty of Design, Architecture and Building.

I acknowledge the International Research Scholarship (UTS IRS) for the financial support towards this research. I would like to thank the Faculty of Design, Architecture and Building, University of Technology Sydney for financially supporting this research. I also acknowledge the support of sustainability and construction professionals who completed the surveys and interviews.

## **DEDICATION**

This thesis is dedicated to God, my mentor Prophet T.B. Joshua, my extended family and generations yet unborn.

# TABLE OF CONTENTS

Acknowledgement.....	ii
Dedication.....	iii
Table of Content.....	iv
List of Figures.....	ix
List of Tables.....	x
Abstract.....	xi
<b>CHAPTER 1 .....</b>	<b>1</b>
1.1 RESEARCH BACKGROUND .....	1
1.2 RESEARCH SIGNIFICANCE .....	3
1.3 RESEARCH PROBLEMS.....	4
1.4 RESEARCH QUESTIONS.....	5
1.5 AIMS AND OBJECTIVES .....	6
1.6 RESEARCH METHODOLOGY .....	7
1.7 OUTLINE OF THESIS .....	9
1.8 SUMMARY .....	11
<b>CHAPTER 2 A CRITICAL REVIEW OF CONSTRUCTION, ENVIRONMENT AND SUSTAINABILITY .....</b>	<b>12</b>
2.0 INTRODUCTION.....	12
2.1 GLOBAL POSITION OF THE CONSTRUCTION INDUSTRY.....	12
2.2 THE CONSTRUCTION INDUSTRY IN AUSTRALIA .....	14
2.3 THE ENVIRONMENT.....	16
2.3.1 Environmental impact of construction.....	17
2.4 OVERVIEW OF SUSTAINABILITY.....	21
2.4.1 Branches of sustainability .....	22
2.4.1.1 Economic sustainability .....	22
2.4.1.2 Social sustainability .....	23
2.4.1.3 Environmental sustainability .....	25
2.4.2 Linking the branches of sustainability .....	27
2.5 SUSTAINABLE DEVELOPMENT .....	30
2.5.1 Sustainable development defined.....	30
2.5.2 Sustainable development concept.....	32
2.5.3 The formation of environmental movements towards sustainable development.....	33
2.5.4 Impact of environmental movements on sustainable development .....	34
2.7 BARRIERS TO SUSTAINABLE CONSTRUCTION .....	40
2.8 ENVIRONMENTAL MANAGEMENT .....	45
2.8.1 The concept of environmental management .....	45
2.8.2 Importance of environmental management.....	47
2.8.3 Challenges facing environmental management .....	49
2.9 SUMMARY .....	51
<b>CHAPTER 3 REVIEW OF SUSTAINABLE UPGRADE OF EXISTING BUILDINGS AND SUSTAINABLE TECHNOLOGY .....</b>	<b>52</b>
3.0 INTRODUCTION.....	52
3.1 EXISTING BUILDINGS .....	53
3.2 ENERGY PERFORMANCE OF EXISTING OFFICE BUILDINGS .....	55
3.3 ENERGY CONSUMPTION OF EXISTING AND BUILDINGS AGE .....	56

3.4 ENERGY ASSESSMENT TOOLS FOR EXISTING BUILDINGS .....	58
3.5 REFURBISHMENT OF EXISTING BUILDINGS .....	60
3.6 SUSTAINABLE UPGRADE OF EXISTING BUILDINGS .....	62
3.6.1 Drivers of sustainable upgrade of existing buildings.....	64
3.7 TECHNOLOGIES FOR SUSTAINABLE UPGRADE OF EXISTING .....	67
3.7.1 Definition and types of sustainable technologies.....	67
3.7.1.1 Building automation.....	68
3.7.1.2 Lighting technologies.....	69
3.7.1.3 Heating, ventilation and air conditioning (HVAC) systems .....	71
3.7.1.4 Sustainable building envelopes .....	75
3.7.1.5 Renewable energy technologies .....	78
3.8 SUSTAINABLE UPGRADE METHODS.....	80
3.8.1 Sustainable upgrade with a single technology .....	80
3.8.1.1 Application of single automation technology for sustainable upgrade .....	80
3.8.1.2 Application of single lighting technology for sustainable upgrade .....	82
3.8.1.3 Application of single heating, ventilation and air conditioning (HVAC) .....	83
technology for sustainable upgrade.....	83
3.8.2 Sustainable upgrade with various technologies .....	84
3.9 BARRIERS TO THE ADOPTION OF SUSTAINABLE TECHNOLOGIES .....	92
3.10 SUMMARY.....	94
<b>CHAPTER 4 DEVELOPMENT OF A CONCEPTUAL FRAMEWORK FOR SUSTAINABLE UPGRADE OF EXISTING BUILDINGS .....</b>	<b>96</b>
4.0 INTRODUCTION.....	96
4.1 THEORETICAL FRAMEWORK.....	96
4.2 REVIEW OF ENERGY PREDICTION METHODS .....	103
4.2.1 Statistical energy prediction methods .....	104
4.2.1.1 Exponential smoothing .....	104
4.2.1.2 Time series methods .....	105
4.2.1.3 Grey time series .....	106
4.2.1.4 Autoregression analysis (ARMA) and integrated/moving average (ARIMA)...	106
4.2.1.5 Regression modelling .....	107
4.2.2 Application of multiple regression for sustainable upgrade of existing .....	108
buildings .....	108
4.2.3 Artificial intelligence methods.....	111
4.2.3.1 Support vector machines.....	111
4.2.3.2 Experts systems and fuzzy logic .....	113
4.2.3.3 Artificial neural networks .....	114
4.3 VARIABLES FOR PREDICTING ENERGY PERFORMANCE OF .....	115
SUSTAINABLE UPGRADE.....	115
4.3.1 Building size .....	115
4.3.2 Building age.....	116
4.3.3 U-value of ceiling and wall .....	117
4.3.4 Thickness of insulation .....	119
4.3.5 Occupancy .....	121
4.3.6 External wall area .....	123
4.3.7 Window size and area .....	125
4.3.8 Type of building .....	126
4.3.9 Climate conditions .....	127
4.3.10 Energy efficient technologies .....	128
4.4 A PREDICTIVE CONCEPTUAL MODEL FOR SUSTAINABLE UPGRADE .....	129
4.4.1 Upgrade of conceptual model towards energy prediction.....	130
4.5 SUMMARY .....	133
<b>CHAPTER 5 RESEARCH METHODOLOGY AND METHODS .....</b>	<b>134</b>
5.0 INTRODUCTION.....	134
5.1 RESEARCH APPROACH.....	134

5.2 RESEARCH DESIGN DEFINED .....	136
5.3 TYPES OF RESEARCH DESIGNS .....	138
5.3.1 Qualitative research.....	138
5.3.2 Quantitative research .....	139
5.3.3 Mixed methods research .....	140
5.4 ADOPTED RESEARCH METHOD .....	142
5.4.1 Questionnaire survey.....	142
5.4.2 Justification for questionnaire survey .....	143
5.4.3 Survey development.....	148
5.5 ANALYSIS OF PILOT STUDY.....	154
5.5.1 Background .....	154
5.5.2 Comments .....	155
5.5.3 Challenges .....	156
5.6 SURVEY SAMPLING PROCEDURES .....	156
5.6.1 Selection of appropriate sampling method for the study.....	157
5.6.2 Towards appropriate sample size .....	158
5.6.3 Sample errors and their corrections .....	160
5.7 SURVEY DATA COLLECTION .....	161
5.7.1 Response rate .....	163
5.7.2 Margin of error .....	164
5.7.3 Data editing .....	165
5.8 QUALITATIVE STRATEGIES.....	165
5.8.1 Interviews .....	166
5.8.1.1 Unstructured interviews.....	166
5.8.1.2 Semi-structured interviews .....	167
5.8.1.3 Structured interviews.....	168
5.9 ADOPTING A QUALITATIVE APPROACH FOR THE STUDY .....	169
5.9.1 Selection of participants for semi-structured interviews .....	171
5.9.2 Semi-structured data collection and procedure .....	172
5.10 CASE STUDY .....	175
5.11 SUMMARY.....	178
<b>CHAPTER 6 ANALYSIS OF DATA FROM SURVEY AND INTERVIEWS.....</b>	<b>180</b>
6.0 INTRODUCTION.....	180
6.1 ANALYSIS OF THE BACKGROUND OF RESPONDENTS.....	180
6.1.1 Gender of respondents .....	181
6.1.2 Age of respondents .....	181
6.1.3 Profession of respondents .....	182
6.1.4 Working experience .....	183
6.1.5 Renovation experience .....	184
6.1.6 Sustainable upgrade experience.....	184
6.1.7 Value of renovation works.....	185
6.2 TECHNOLOGIES USED FOR SUSTAINABLE UPGRADE .....	186
6.3 RELATIONSHIP BETWEEN SUSTAINABLE TECHNOLOGY AND .....	188
BUILDING AGE .....	188
6.3.1 Chi-square test analysis.....	192
6.4 IDENTIFICATION OF INDEPENDENT VARIABLES FOR PREDICTIVE.....	193
MODEL .....	193
6.4.1 Analysis of variables related to existing buildings .....	193
6.4.2 Analysis of sustainable technology related variables .....	198
6.4.3 T-test statistics for extraction of independent variables .....	198
6.5 FACTOR ANALYSIS OF SUSTAINABLE TECHNOLOGIES .....	206
6.5.1 Component (factor) extraction .....	208
6.6 ANALYSIS OF SEMI-STRUCTURED INTERVIEWS.....	215
6.6.1 Reasons for low installation of sustainable technologies for.....	217
sustainable upgrade .....	217

6.6.1.1 Perceived gains in demolish and rebuild .....	217
6.6.1.2 Age of building .....	218
6.6.1.3 Tenants .....	219
6.6.1.4 Perceived hidden cost .....	220
6.6.1.5 Overall cost of refurbishment.....	221
6.6.1.6 Aesthetic considerations .....	222
6.6.2 Challenges faced introducing technologies for sustainable .....	223
building upgrade of existing buildings .....	223
6.6.2.1 Building type .....	223
6.6.2.2 Existing building elements.....	225
6.6.2.3 Building age .....	226
6.6.2.4 Existing infrastructure.....	228
6.6.2.5 Cost of sustainable technologies .....	229
6.7 SUMMARY .....	230
<b>CHAPTER 7 DEVELOPMENT OF A PREDICTIVE MODEL FOR SUSTAINABLE</b>	
<b>UPGRADE OF EXISTING BUILDINGS .....</b>	<b>231</b>
7.0 INTRODUCTION.....	231
7.1 PREDICTIVE MODELLING .....	232
7.2 APPLYING REGRESSION MODELLING WITH FACTOR ANALYSIS .....	233
7.3 REGRESSION ANALYSIS .....	235
7.3.1 Simple linear regression analysis.....	236
7.3.2 Multiple regression analysis.....	237
7.3.2.1 Justification for adoption of multiple regression approach .....	239
7.4 MODEL DEVELOPMENT.....	241
7.4.1 Test of collinearity, stationery and normal distribution.....	241
7.4.2 Variable selection for the model.....	242
7.4.3 Interpretation of model results .....	245
7.5 ADOPTION OF MODEL .....	247
7.5.1 Predictive model and variables selected .....	248
7.5.2 The model equation .....	251
7.6 MODEL ADEQUACY.....	254
7.6.1 Tolerance and variance inflation factor .....	254
7.6.2 Residual analysis.....	257
7.7 SUMMARY .....	262
<b>CHAPTER 8 DISCUSSION OF MAIN FINDINGS .....</b>	<b>264</b>
8.0 INTRODUCTION.....	264
8.1 TECHNOLOGIES FOR SUSTAINABLE UPGRADE.....	264
8.2 RELATIONSHIP BETWEEN SUSTAINABLE TECHNOLOGY AND .....	267
BUILDING AGE .....	267
8.3 FACTORS INFLUENCING ENERGY CONSUMPTION – PREDICTIVE .....	269
8.3.1 Relationship between building size and energy consumption .....	271
8.3.2 Relationship between window size and energy consumption.....	272
8.3.3 U–value of wall and ceiling and energy consumption.....	273
8.3.4 Relationship between external wall area and energy consumption .....	275
8.3.5 Relationship between thickness of insulation and energy consumption .....	277
8.3.6 Relationship between number of occupants and energy consumption.....	278
8.3.7 Relationship between building age and energy consumption.....	280
8.3.8 Relationship between wind speed and energy consumption .....	281
8.3.9 Relationship between sustainable lighting and automation .....	283
technologies and energy consumption.....	283
8.3.10 Sustainable HVAC systems and energy consumption .....	285
8.3.11 Sustainable HVAC equipment and energy consumption.....	287
8.3.12 Relationship between sustainable envelope and energy consumption.....	288
8.3.13 Impact of renewable technologies on energy consumption .....	290
8.3.14 Relationship between passive technologies and energy consumption .....	291



8.3.15 Life span of sustainable technology and energy consumption .....	292
8.4 SUMMARY .....	294
<b>CHAPTER 9 VALIDATION OF PREDICTIVE MODEL FOR EXISTING BUILDINGS UPGRADED WITH SUSTAINABLE TECHNOLOGIES .....</b>	<b>295</b>
9.0 INTRODUCTION .....	295
9.1 VALIDATION PROCESSES .....	296
9.1.1 Validation defined .....	296
9.1.2 Validation types and selection .....	298
9.1.2.1 External validation .....	300
9.3 APPLICATION OF ADOPTED VALIDATION METHODS .....	305
9.4 CASE STUDY VALIDATION .....	311
9.4.1 Selection of case study: educational building .....	312
9.4.2 Data collection and analysis .....	316
9.4.3 Refurbishment with sustainable technologies .....	318
9.4.4 Testing of the model equation .....	322
9.5 SUMMARY .....	325
<b>CHAPTER 10 CONCLUSIONS AND RECOMMENDATIONS .....</b>	<b>326</b>
10.0 INTRODUCTION .....	326
10.1 RESEARCH QUESTIONS .....	326
10.2 REVIEW OF OBJECTIVES .....	327
10.3 CONCLUSIONS .....	332
10.4 LIMITATION OF FINDINGS .....	334
10.5 RECOMMENDATION FOR FUTURE STUDIES .....	335
10.6 RECOMMENDATION FOR INDUSTRY .....	337
10.7 SUMMARY .....	339
REFERENCES AND BIBLIOGRAPHY .....	340

## LIST OF FIGURES

Figure 1.1: Outline of thesis .....	10
Figure 2.1: Global population growth.....	13
Figure 2.2: History and projections of energy use .....	15
Figure 2.3: Environmental cycle adopted from Hammond (1995).....	16
Figure 2.4: Estimates of global resources used in building (%) .....	18
Figure 2.5: Impact of construction on the environment.....	21
Figure 2.6: Relationship among branches of sustainability .....	28
Figure 2.7: Environmental management processes .....	46
Figure 3.1: Total energy consumption by building type in Australia in 2009.....	55
Figure 4.1: Energy saving and energy efficiency .....	100
Figure 4.2: Technology, building age and energy savings.....	103
Figure 4.3: Technology and energy characteristics .....	130
Figure 4.4: Upgraded conceptual model .....	131
Figure 6.1: Overall sustainable technologies.....	187
Figure 6.2: Key sustainable technologies.....	187
Figure 6.3: Summary of highly ranked means .....	196
Figure 6.4: Scree plot of factors .....	210
Figure 7.1: Normal P-P plot.....	260
Figure 7.2: Histogram of residuals.....	261
Figure 7.3: Scatter diagram.....	262
Figure 8.1: Established relationships.....	270
Figure 9.1: North view of case study building (left) .....	316
Figure 9.2: Atrium of case study building (right) .....	316
Figure 9.3: Energy consumption before first sustainable upgrade .....	318
Figure 9.4: Energy consumption after first sustainable upgrade .....	319
Figure 9.4: Energy consumption after second sustainable upgrade .....	321

## LIST OF TABLES

Table 2.1: Output and employment in Australia (2015-2016).....	14
Table 3.1: Energy assessment tools .....	59
Table 3.2: Comparison of rating systems .....	60
Table 3.3: Stages of refurbishment .....	61
Table 3.4: Sustainable technologies used to upgrade existing buildings .....	90
Table 5.1: Comparison of methods .....	138
Table 5.2: Research questions and associated methods .....	142
Table 5.3: Advantages and disadvantages of interviews .....	169
Table 6.1: Gender of respondents.....	181
Table 6.2: Age of respondents .....	182
Table 6.3: Profession of respondents.....	183
Table 6.4: Working experience of respondents .....	184
Table 6.5: Renovation experience.....	184
Table 6.6: Sustainable upgrade experience .....	185
Table 6.7: Overall value of sustainable upgrade.....	186
Table 6.8: Relationship between building age and sustainable technology .....	190
Table 6.9: Chi square results .....	192
Table 6.10: Ranking of sustainable technology variables .....	195
Table 6.11: One sample t-test.....	201
Table 6.12: Ranking of variables (2-tailed).....	202
Table 6.13: Ranking of variables (1-tailed).....	204
Table 6.14: Cronbach's test of reliability.....	207
Table 6.15: KMO and Bartlett's test.....	208
Table 6.16: Total variance explained.....	209
Table 6.17: Communalities .....	212
Table 6.18: Component matrix .....	213
Table 6.19: Overall variables.....	214
Table 7.1: Model summary.....	245
Table 7.3: Significant variables .....	250
Table 7.4: Collinearity statistics.....	257
Table 9.1: Test parameters .....	311
Table 9.2: Case study education building test variables .....	323
Table 9.3: Case study education building validation results.....	324

## **ABSTRACT**

The impact of existing buildings on the environment is increasing. There is the need to realign and focus on achieving true sustainability that considers sustainable technologies for built facilities. However, these technologies with varying functions become outdated over time, thus there is the need to upgrade to match new energy efficiency benchmarks. The sustainable upgrade of existing buildings adopts sustainable technologies to reduce the impact of high energy consumption and greenhouse gas emissions. This thesis develops a predictive model to estimate energy consumption of existing buildings upgraded with sustainable technologies. The study investigates the types of sustainable technologies, and the relationship between sustainable technologies and building age, and variables impacting energy consumption of existing buildings. A literature review of the need for sustainable development to curb the increasing impact of existing buildings on the environment, including the nature of existing buildings, types of sustainable renovation and related energy savings, drivers of sustainable upgrade, sustainable technologies and barriers to the adoption and application of sustainable technologies is followed by a review of tools used to predict energy consumption of existing buildings improved with sustainable technologies. A conceptual framework for sustainable upgrade is developed to present the determinants of existing buildings and sustainable technologies in predicting the energy consumption through sustainable upgrade. The methodology is a mixed method approach including a questionnaire with in-built case study, interviews and verification through case study.

The findings indicate that sustainable technologies adopted to improve existing buildings are less expensive, leading to less energy reduction. Also, sustainable technologies required to improve energy savings only target fairly new buildings with a majority of old buildings not receiving the same investment. The main variables identified as contributing to energy consumption in existing buildings are building size, window area, area of external wall, number of occupants, U-value of ceiling and walls, thickness of insulation and lifespan of sustainable technologies. The main energy saving technologies are lighting technologies, HVAC, renewable energy technologies, envelope technologies, sustainable HVAC equipment and passive technologies. The predictive model combines the main determinants into an energy efficient decision tool to support sustainable upgrade of existing buildings. It makes it possible to calculate expected energy savings from upgrades of existing buildings with sustainable technologies, presenting a clear direction for energy savings which ultimately also translate into cost savings.